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# OPTICAL POLARIMETRIC PROPERTIES OF THE MATERIALS IN THE PAGEOS I AND ECHO II SATELLITE SURFACES


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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1970

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM X-2089 | | |

| | |
|---|---|
| 4. Title and Subtitle<br>OPTICAL POLARIMETRIC PROPERTIES OF THE MATERIALS IN THE PAGEOS I AND ECHO II SATELLITE SURFACES | 5. Report Date<br>September 1970 |
| | 6. Performing Organization Code |
| 7. Author(s)<br>Robert Benjamin Lee III | 8. Performing Organization Report No.<br>L-6749 |
| 9. Performing Organization Name and Address<br>NASA Langley Research Center<br>Hampton, Va. 23365 | 10. Work Unit No.<br>124-09-26-01 |
| | 11. Contract or Grant No. |
| | 13. Type of Report and Period Covered<br>Technical Memorandum |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract


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| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Polarization<br>Reflectance<br>Amorphous phosphate coating<br>Aluminum | Unclassified – Unlimited |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 15 | $3.00 |

*For sale by the Clearinghouse for Federal Scientific and Technical Information
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# OPTICAL POLARIMETRIC PROPERTIES OF THE MATERIALS IN THE PAGEOS I AND ECHO II SATELLITE SURFACES

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## SUMMARY

Laboratory measurements were made of the percent polarization of light reflected from materials representative of those in the PAGEOS I and Echo II satellite surfaces. The percent polarization was determined as a function of phase angle (angle between the incident and reflected light) from $10^{\circ}$ to $168^{\circ}$ in the ultraviolet, blue, and visual spectral bands. The PAGEOS I surface material was vapor-deposited aluminum on poly(ethylene terephthalate) film (PET), whereas the Echo II surface had an alodine (amorphous phosphate) coating chemically formed to a rolled aluminum-foil substrate. The polarization for the PAGEOS I surface was found to be in agreement with that calculated for vapor-deposited aluminum. The polarization for the Echo II surface was found to be greater than that for the rolled aluminum-foil substrate, both being dependent upon the orientation of the substrate line structure with respect to the plane of incidence.

## INTRODUCTION

The PAGEOS I (Passive Geodetic Earth Orbiting Satellite) is a 30.48-meter-diameter inflatable aluminized balloon of poly(ethylene terephthalate) film (hereinafter called PET) with a highly reflective surface. It was launched in 1966 as part of the National Geodetic Satellites Program (ref. 1). The Echo II satellite is a 41.15-meter-diameter inflatable balloon with an alodine (amorphous phosphate) coating formed to a rolled aluminum-foil surface. It was launched in 1964 as part of a passive satellites communication program (ref. 2).

Sunlight incident upon the PAGEOS I and Echo II surfaces becomes partially polarized upon reflection. The degree of polarization is dictated by the optical surface properties of the satellites and the phase angle (angle between the incident and reflected light) of the reflected sunlight. Therefore, ground-based polarimetric observations of the satellites were initiated in 1967 to determine from variations in the polarization the effects of long-term exposure of their surfaces to the space environment. In the observations, the percent polarization of the sunlight reflected from each satellite was measured by the

Satellite Photometric Observatory (ref. 3) as a function of phase angle in the ultraviolet, blue, and visual spectral bands.

In order to assist in the analysis of the ground-based polarimetric measurements of these satellites, laboratory measurements were made of the percent polarization of light reflected from materials representative of these satellites. The laboratory measurements were performed by using optical techniques similar to those used in the satellite observations, and the results are given in this report.

## SYMBOLS

The units used for the physical quantities defined in this paper are given in the International System of Units (SI). Factors relating this system to U.S. Customary Units are given in reference 4.

$k_o$ coefficient of absorption

$L_{max}$ maximum illumination, measured behind a rotating linear analyzer, lumen/centimeters$^2$

$L_{min}$ minimum illumination, measured behind a rotating linear analyzer, lumen/centimeter$^2$

N complex index of refraction

n real index of refraction

P polarization, percent

$\Theta$ Principal Angle of Incidence, degrees

$\theta_\rho$ Brewster's angle, degrees

$\theta_1$ angle of incidence, measured between incident light and surface normal, degrees

$\theta_1'$ angle of reflection, measured between specularly reflected light and surface normal, degrees

$\theta_2$ angle of refraction, measured between refracted light and surface normal, degrees

$\rho_y$ reflected fraction of incident light vibrating perpendicular to the plane of incidence

$\rho_\omega$ reflected fraction of incident light vibrating parallel to the plane of incidence

$\psi$ phase angle, measured between incident and reflected light, degrees

## THEORY

Dielectrics and metals introduce linear and elliptical polarization, respectively, to reflected light. The dominant vibration direction of the reflected light is generally perpendicular to the plane of incidence. The percent polarization P of the specularly reflected light can be calculated by means of the equation for polarization which is

$$P = \frac{\rho_y - \rho_\omega}{\rho_y + \rho_\omega} \times 100 \text{ percent} \tag{1}$$

where $\rho_y$ and $\rho_\omega$ are the reflected fractions of the incident light vibrating perpendicular and parallel, respectively, to the plane of incidence.

For optically smooth dielectrics, $\rho_y$ and $\rho_\omega$ can be described by Fresnel's formulas (ref. 5) as

$$\rho_y = \left[\frac{-\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}\right]^2 \tag{2}$$

and

$$\rho_\omega = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}\right]^2 \tag{3}$$

where $\theta_1$ and $\theta_2$ are the angles of incidence and refraction, respectively. By applying Snell's Law where $n = \sin\theta_1/\sin\theta_2$, equations (2) and (3) are modified to

$$\rho_y = \left(\frac{\cos\theta_1 - n\cos\theta_2}{\cos\theta_1 + n\cos\theta_2}\right)^2 \tag{4}$$

and

$$\rho_\omega = \left(\frac{n\cos\theta_1 - \cos\theta_2}{n\cos\theta_1 + \cos\theta_2}\right)^2 \tag{5}$$

where n is the real index of refraction. For equation (5), $\rho_\omega$ becomes zero when $\theta_1 + \theta_2 = 90^\circ$ (where $\theta_2$ is related to $\theta_1$ by Snell's Law), thus leaving the reflected

light completely plane-polarized perpendicular to the plane of incidence. The angle of incidence where this occurs is called Brewster's angle $\theta_\rho$ and is defined as

$$\theta_\rho = \tan^{-1} n \tag{6}$$

For angles of incidence other than Brewster's angle the reflected light is partially plane polarized.

For optically smooth metals, $\rho_y$ and $\rho_\omega$ can be calculated by substituting the complex index of refraction, $N = n - ik_o$, for $n$ in equations (4) and (5), where $k_o$ is the coefficient of absorption. (See ref. 5.) The resulting equations are

$$\rho_y = \frac{\left(n - \cos \theta_1\right)^2 + k_o^2}{\left(n + \cos \theta_1\right)^2 + k_o^2} \tag{7}$$

and

$$\rho_\omega = \frac{\left(n - \frac{1}{\cos \theta_1}\right)^2 + k_o^2}{\left(n + \frac{1}{\cos \theta_1}\right)^2 + k_o^2} \tag{8}$$

In analogy to Brewster's angle, the angle of incidence for metals where $\rho_\omega$ is a minimum, but not zero, is called the Principal Angle of Incidence $\Theta$. Reflected light for metals, incident at $\Theta$, is elliptically polarized.

When the reflecting surface consists of a semitransparent dielectric coated to a metal, it would be expected that the reflected light would be a combination of linear polarization from the dielectric and elliptical polarization from the metal. In addition, there are interference effects to consider when the incident light is of the order of the coating thickness.

## TEST MATERIALS

The materials investigated are representative of those used in the PAGEOS I (ref. 6) and the Echo II (ref. 7) satellite surfaces.

### PAGEOS I

The PAGEOS I material is 0.2-$\mu$m-thick aluminum vapor-deposited on one side of a 12.70-$\mu$m-thick PET film. The reflecting surface is the aluminum.

### Echo II

The Echo II material is an alodine (amorphous phosphate) coating chemically formed on the outer surfaces of an aluminum-PET-aluminum substrate. The alodine,

a semitransparent dielectric, has an average surface density of $1.99 \times 10^{-4}$ gm/cm$^2$. The substrate is composed of 8.89-$\mu$m-thick PET film adhesively bonded between two layers of 4.57-$\mu$m-thick rolled aluminum foil. The foil has a fine line structure (see fig. 1) that results from rolling aluminum in thin gages (ref. 8). The line structure gives the Echo II surface roughly the geometry of a reflection diffraction grating. The reflecting surface is the alodine-coated aluminum foil.

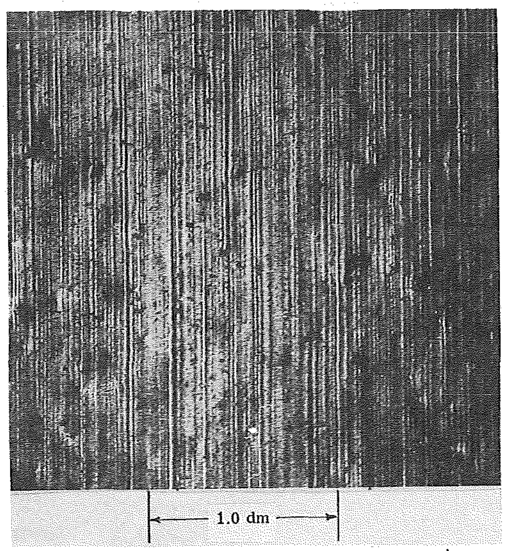


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Figure 1.- Micrograph of the Echo II aluminum-foil substrate, illustrating the surface line structure. Micrograph made in oblique light at 50× magnification.

Both materials were placed in a sample holder, resembling an embroidery hoop, under stress to obtain flat reflecting surfaces.

## TEST APPARATUS

The polarization measurements were made by using an optical bench photometer which is a monoplane goniophotometer equipped with linear polarization analyzers. The optical bench photometer is shown in figure 2, and a schematic diagram of the light path is shown in figure 3. The output of the source is passed through an aperture stop, collimated into a 0.635-cm-diameter beam by a collimating lens, and then filtered by a color filter before striking the test material. The light, specularly $\left(\theta_1 = \theta_1'\right)$ reflected from the test material at a preselected phase angle, is then passed through a rotating linear analyzer, a field stop, depolarizer, and then is focused onto the photomultiplier-tube entrance slit by a condensing lens. A description of the photometer components is given in table I.

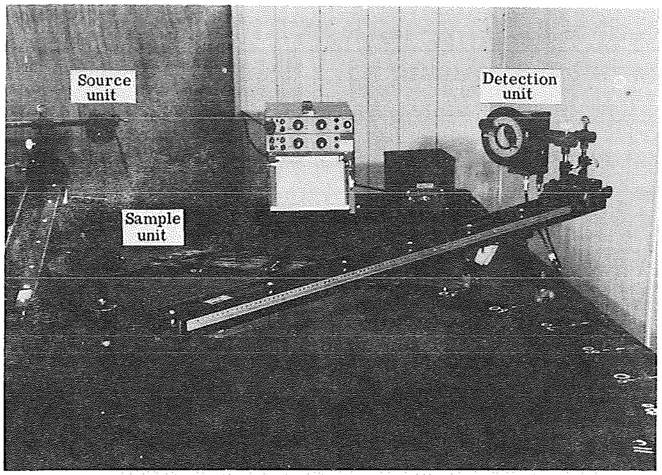


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Figure 2.- Optical bench photometer.

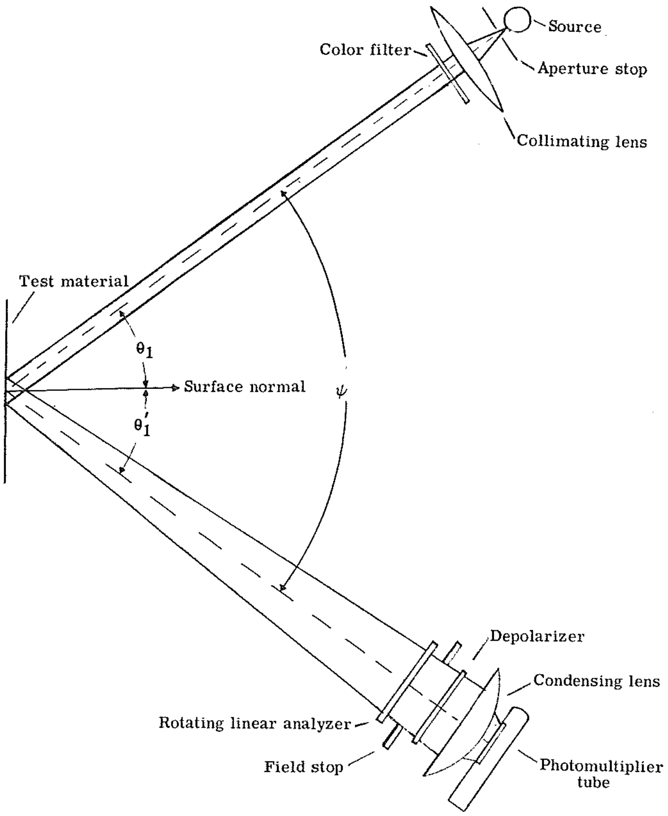



Figure 3.- Light path in the optical bench photometer.

TABLE I.- COMPONENTS OF OPTICAL BENCH PHOTOMETER

| Component | Description |
|---|---|
| Source . . . . . . . . . . . . . | Zirconium-concentrated arc lamp |
| Aperture stop . . . . . . . . | 0.1-cm-diameter opening |
| Collimating lens . . . . . . . | Fused quartz; focal length, 10.00 cm |
| Color filter . . . . . . . . . . . | Standard astronomical ultraviolet, blue, and visual |
| Rotating linear analyzer . . . | HNB'P (ultraviolet) and HN38 (blue and visual) |
| Field stop . . . . . . . . . . . | 2.0-cm-diameter opening |
| Depolarizer . . . . . . . . . . | Two calcite disks, 0.15 and 0.20 cm thick, cemented with their optical axes at $45^{\circ}$ |
| Condensing lens . . . . . . . | Fused quartz; focal length, 8.30 cm |
| Photomultiplier tube . . . . . | S-4 response |

The photometer has stationary and movable arms which permit phase-angle settings from $10^{\circ}$ to $168^{\circ}$, and also a turntable connected to the sample holder to vary the angle of incidence from $-90^{\circ}$ to $90^{\circ}$.

The percent polarization $P$ of the light reflected from test surfaces was determined by substituting the maximum and minimum illuminations, $L_{max}$ and $L_{min}$, respectively, measured behind the rotating linear analyzer into the following equation:

$$P = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \times 100 \text{ percent} \tag{9}$$

The illuminations $L_{max}$ and $L_{min}$ correspond to $\rho_y$ and $\rho_\omega$, respectively. This was the same method used to measure the percent polarization for the PAGEOS I and Echo II by using the NASA Satellite Photometric Observatory. The laboratory measurements were made in the ultraviolet, blue, and visual spectral bands centered around wavelengths of 0.36, 0.44, and 0.55 $\mu$m, respectively, and were confined to the plane of incidence.

The polarization introduced by the test apparatus was determined by measuring the polarization of light reflected from zinc crown glass and comparing it to that calculated for the glass. The two sets of data are compared in figure 4 where the percent polarization $P$ is plotted against phase angle $\psi$ for the visual band. The theoretical polarization was calculated by using equations (1), (4), and (5) and by assuming that $n = 1.52$ for the glass. The comparison shows good agreement between theory and experiment. Therefore, the test apparatus appears to produce reasonable polarization measurements.

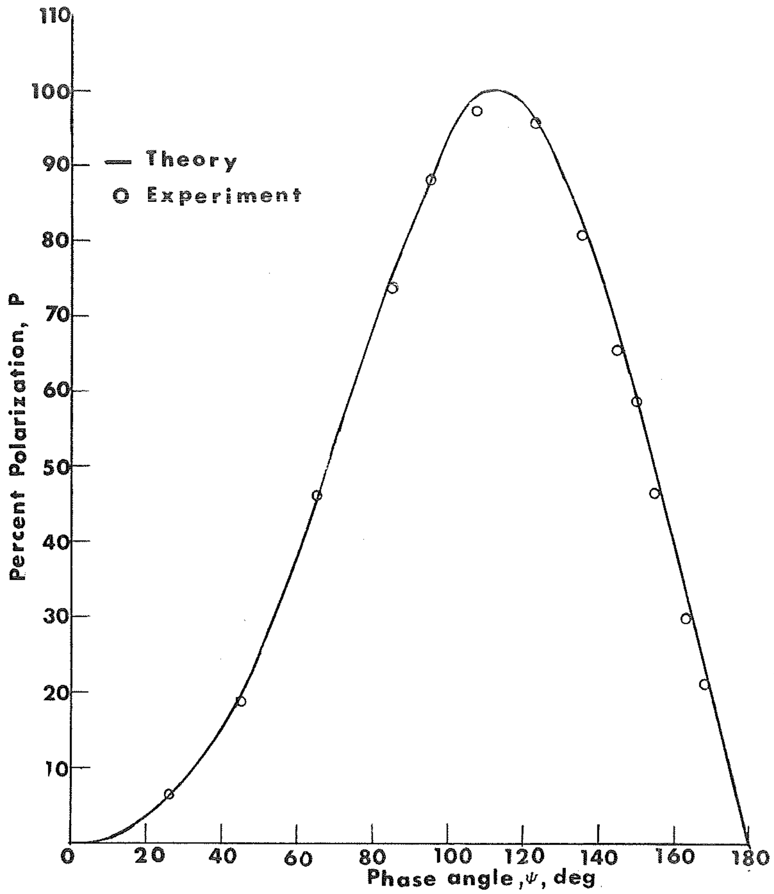


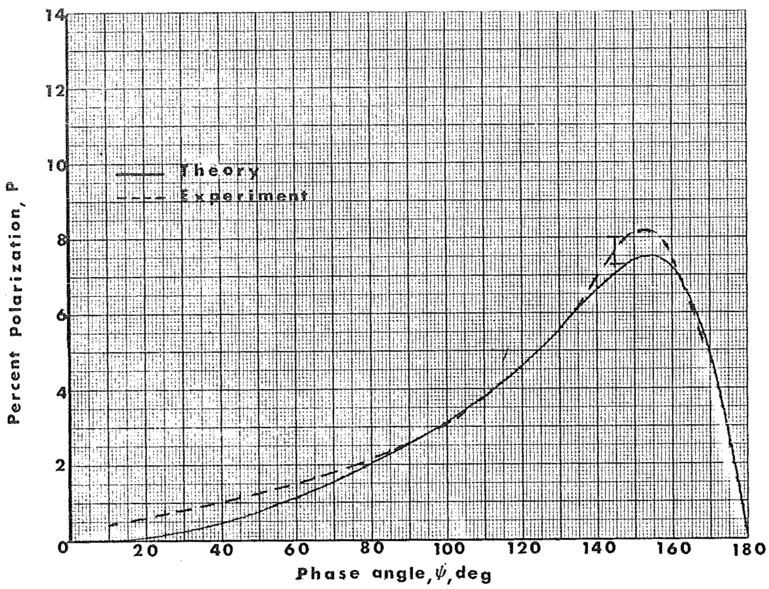

Figure 4.- Polarization of light reflected from zinc crown glass. $n = 1.52$.

## RESULTS AND DISCUSSION

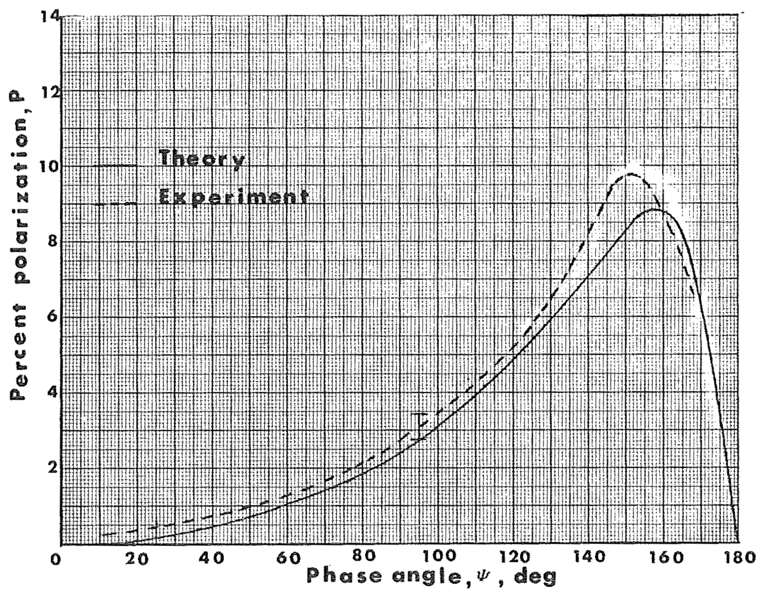
The experimental polarization data represent averages of three to five measurements of a given test material; the typical data spread from the average is indicated by a bar on each curve. The polarization data are presented as a function of phase angle in the ultraviolet, blue, and visual spectral bands.

### PAGEOS I Surface Material

In figure 5 the percent polarization for the PAGEOS I material is presented and compared with that calculated for vapor-deposited aluminum. The theoretical polarization for the vapor-deposited aluminum film was calculated by using equations (1), (7), and (8). This calculation was made by assuming the following optical constants (ref. 9): $n = 0.34$, $k_o = 4.01$; $n = 0.47$, $k_o = 4.84$; and $n = 0.82$, $k_o = 5.99$ for wavelengths of 0.36, 0.44, and 0.55 $\mu$m, respectively. The comparison indicates that the PAGEOS I

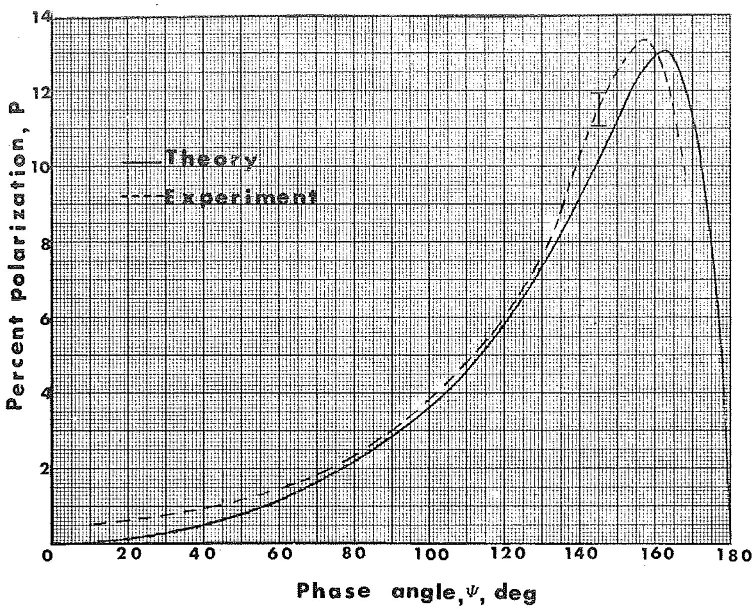



(a) Ultraviolet spectral band.




(b) Blue spectral band.

Figure 5.- Polarization in the specular direction $(\psi = 2\theta_1)$ for the PAGEOS I material. Bars indicate typical spread of data.




(c) Visual spectral band.

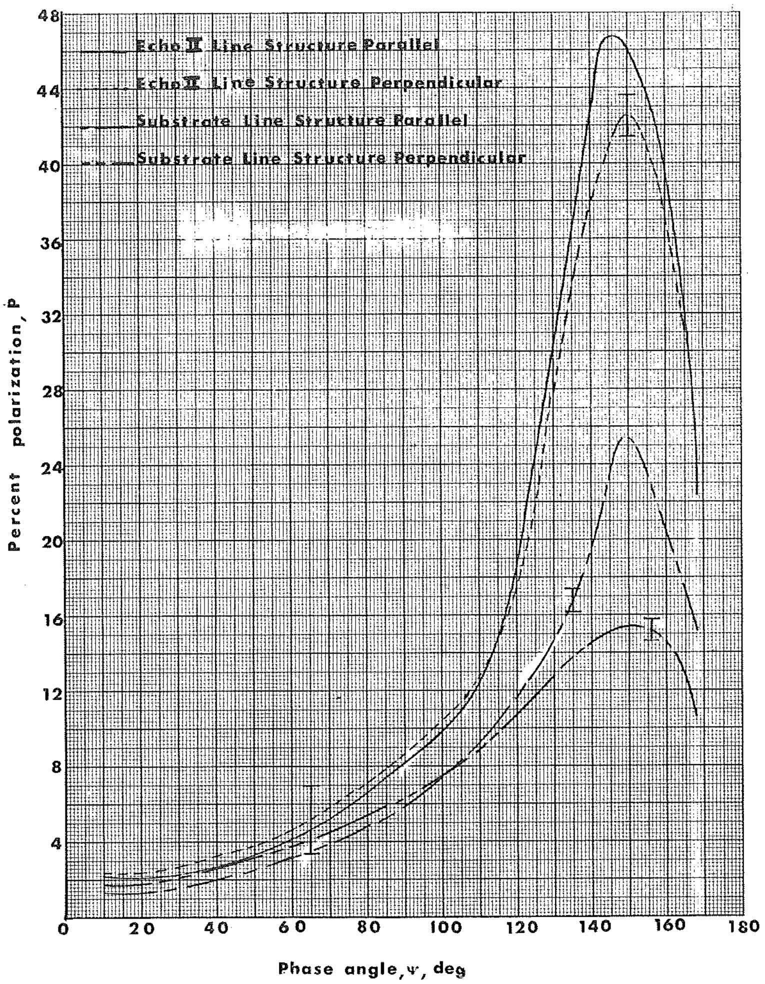
Figure 5.- Concluded.

polarization agrees with that for vapor-deposited aluminum within ±1 percent polarization (10 percent of the maximum polarization), and that the polarization increases with increasing wavelength and peaks at high phase angles.

## Echo II Surface Material

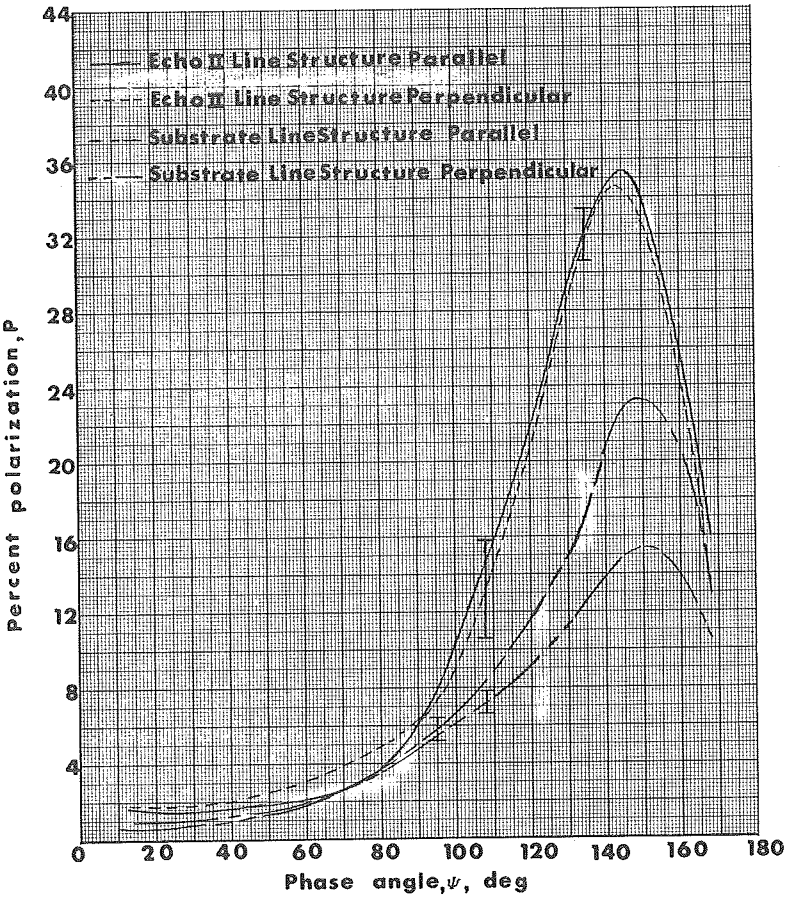
In figure 6 the percent polarization of light reflected from both the Echo II (alodine coated) and the aluminum-foil substrate is presented for the substrate line structure oriented parallel and perpendicular to the plane of incidence. The data for both the coated material and substrate illustrate that the polarization is dependent upon the orientation of the substrate line structure. For low phase angles, the polarization was found to be slightly greater with the surface line structure oriented perpendicular to the plane of incidence than with it parallel. However, for high phase angles, the polarization was found to be greater when the line structure was oriented parallel to the plane of incidence than when it was perpendicular. The results for low phase angles agree with trends expected for reflection diffraction gratings (refs. 10 and 11). The results for high phase angles are, at present, unexplained. The differences in polarization attributed to the orientation of the line structure are less for the Echo II material than for the aluminum substrate.

As shown in figure 6, the Echo II material polarizes the incident light to a greater degree than the aluminum substrate in each spectral band. The maximum differences in



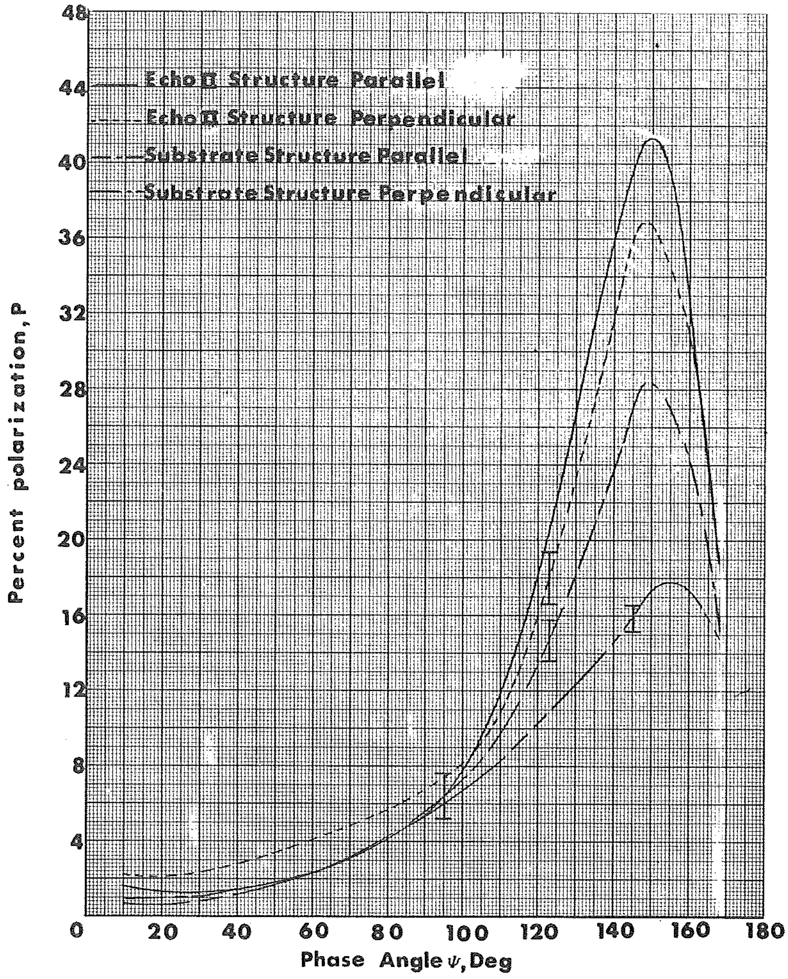

(a) Ultraviolet spectral band.

Figure 6.- Polarization in the specular direction $(\psi = 2\theta_1)$ for the Echo II material. Bars indicate typical spread of data.




(b) Blue spectral band.

Figure 6.- Continued.




(c) Visual spectral band.

Figure 6.- Concluded.

the polarization between the two materials occurred at high phase angles around twice the Principal Angle of Incidence for the substrate. The phase angles of maximum polarization for the Echo II material occurred at values typical of metals.

The Echo II material polarized the incident light in increasing amounts in the blue, visual, and ultraviolet bands. The material absorbed light in increasing amounts in the same order of spectral bands (ref. 7), thus suggesting a relationship between the polarization and surface absorptance.

## CONCLUSIONS

Laboratory measurements were made of the percent polarization of light reflected from materials representative of those in the PAGEOS I and Echo II satellite surfaces. The following conclusions are presented:

1. The PAGEOS I material polarized the incident light upon reflection in increasing amounts with wavelength; the resulting polarization agreed with that calculated for vapor-deposited aluminum.

2. At low phase angles the polarization of incident light reflected from both the Echo II material and its aluminum substrate was found to be slightly greater with the substrate surface line structure oriented perpendicular to the plane of incidence than with it parallel. However, for high phase angles, polarization was found to be greater when the line structure was oriented parallel to the plane of incidence than when it was perpendicular.

3. The Echo II material polarized the incident light to a much greater degree than its aluminum substrate, and in increasing amounts in the blue, visual, and ultraviolet spectral bands. As typical for metals, the polarization for the Echo II material peaked at high phase angles.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 14, 1970.

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